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Domain structure of EuS/PbS and EuS/YbSe superlattices studied by polarized neutron reflectometry

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Abstract

Polarized neutron reflectivity experiments have been carried out on a number of specimens of ferromagnetic (FM) semiconductor superlattices EuS/PbS and EuS/YbSe with (0 0 1) growth plane in order to determine the distribution of magnetization directions of the in-plane FM domains. A preferred magnetic domain orientation within the growth plane was found in all the samples investigated.

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The all-semiconductor superlattice (SL) systems EuS/PbS and EuS/YbSe exhibit a range of intriguing magnetic properties. Neutron reflectivity data from these structures show the existence of pronounced antiferromagnetic (AFM) exchange coupling between the ferromagnetic EuS layers across the nonmagnetic, and virtually nonconducting PbS and YbSe spacers [1].

Specular [2] and off-specular [3] polarized neutron reflectometry (PNR) has recently been used to get an insight into the lateral magnetic structure in thin films and SLs.

In this paper, we present specular PNR results that reveal the in-plane domain structure and in-plane magnetic anisotropy in the EuS layers.

Typical reflectivity spectra from the systems are displayed in Fig. 1. The structural SL Bragg maximum (purely nuclear) is seen only in the non-spin-flip (NSF) modes showing no splitting between (++) and (−−) cross-sections. A purely magnetic "half-order" maximum, arising from AFM interlayer coupling, shows a pronounced asymmetry in the NSF and spin-flip (SF) intensities. This clearly indicates that the in-plane domain states allowed by the fourfold crystallographic symmetry of the (0 0 1)EuS epitaxial layers are not uniformly populated.

The first data set presented was obtained from a EuS/PbS SL sample with a 4.5 Å PbS spacer. This sample was found to exhibit the strongest

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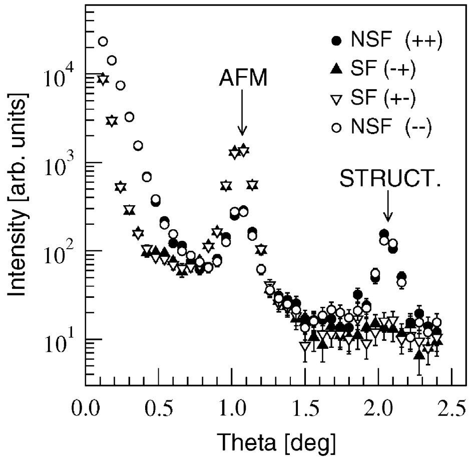

Fig. 1. Polarized neutron reflectivity profiles for a EuS/YbSe (46 Å/20 Å) × 15 SL with the in-plane [1 1 0] axis horizontal.

interlayer coupling ever observed in any EuS/PbS SL. In Fig. 2 the polarization analysis of the first "half-order" SL maximum is shown for three different sample orientations. Figs. 2(a) and (b) show, respectively, the data from measurements in which the [1 1 0] and [1 0 0] high-symmetry in-plane axes were aligned vertically. In both cases there is quite a large difference in the NSF and SF reflected intensities. In principle, this can stem either from nonuniform magnetic domain distribution in the growth plane, or from the fact that there is only a *single* preferred orientation axis, making some angle with the neutron polarization axis. In the latter case, by rotating the sample about the normal to its surface, one should be able to find a "special" alignment of the magnetization direction with respect to the polarization axis (vertical in our experiments) that would allow an unambiguous determination of that direction. Essentially, there might be two such "special" orientations, with the unique direction vertical, or horizontal. In the first case all the scattering should be NSF, in the second only SF.

Another special case is when all the NSF and SF intensities are equal. The latter situation is shown in Fig. 2(c). Here the sample was rotated 19° from the [1 0 0]-vertical position. In this new alignment it is the [2 1 0] axis that makes a 45° angle with the vertical direction. This may be indicative of a

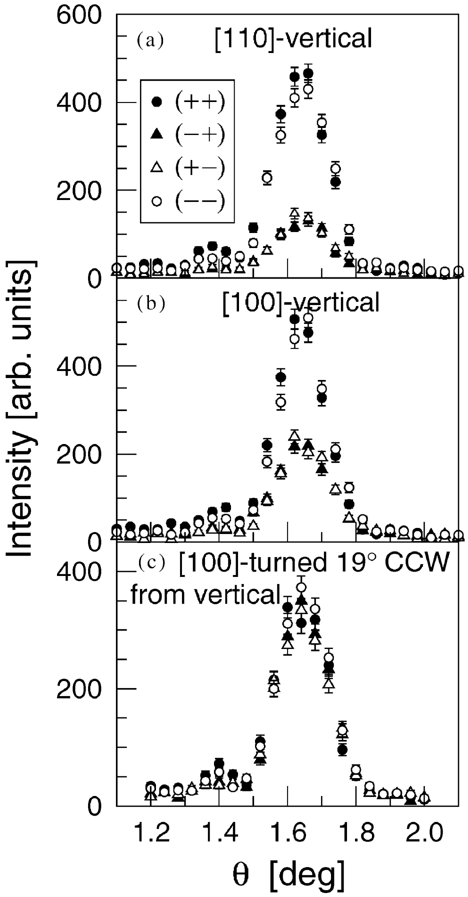

Fig. 2. Polarization analysis of the AFM SL Bragg peak for EuS/PbS (30 Å/4.5 Å) × 15 SL for different sample orientations.

uniaxial sample with all the domains aligned along the [2 1 0] direction, or there might be also some domains oriented along the perpendicular [1 $\bar{2}$ 0] axis.

To see whether both [2 1 0] and [1 $\bar{2}$ 0] directions are populated by magnetic domains, and what their relative population is, the sample was remounted with the [2 1 0] axis in horizontal position. A series of measurements was then carried out with the sample rotated about the normal to its reflecting surface by ±20° from this position. The results are presented in Fig. 3(a).

Analogous data obtained for a EuS/YbSe SL mounted with the [1 0 0] in-plane axis vertical are shown in Fig. 3(b). Here again, all four polarized neutron reflectivities R^{++}, R^{-+}, R^{+-}, and R^{--}

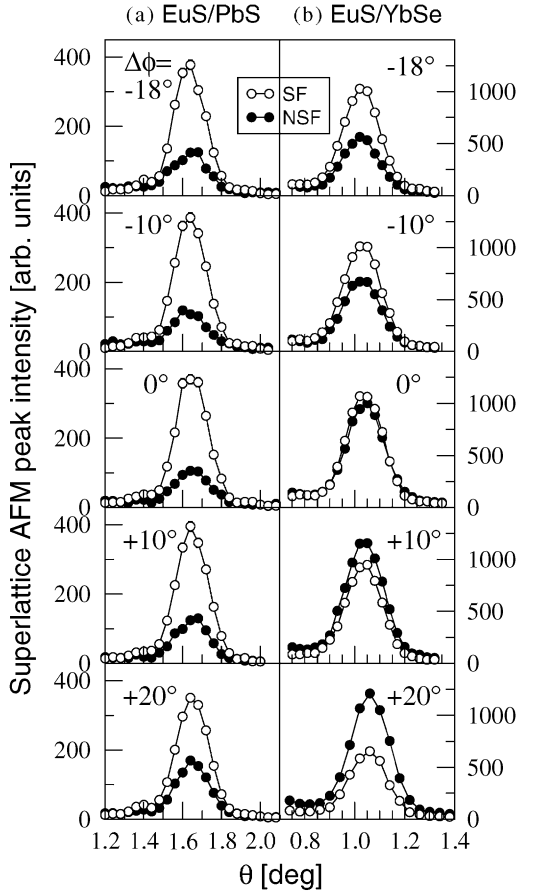

Fig. 3. The NSF and SF intensities of the AFM SL Bragg peaks for different alignments of the samples with respect to the neutron polarization direction: (a) EuS/PbS with [2 1 0] axis, and (b) EuS/YbSe with [0 1 0] axis in horizontal (when $\Delta\phi = 0$) positions.

are nearly equal (see the panel marked $\Delta\phi = 0$ in Fig. 3(b)). Thus, for this sample the [1 1 0] and [1 $\bar{1}$ 0] in-plane directions are the easy axes along which the magnetizations are aligned.

To explain the observed effects it was assumed that the samples consist of two types of domains with their magnetizations aligned along two perpendicular directions, [1 1 0] and [1 $\bar{1}$ 0] in the case of EuS/YbSe specimen, and [2 1 0] and [1 $\bar{2}$ 0] in EuS/PbS sample. The area of the sample occupied by these domains is $S_1 = xS$ and $S_2 = (1-x)S$, respectively, where S is the total reflecting area of the sample (see Fig. 4). It can be shown, that the ratio of NSF to SF intensities from such

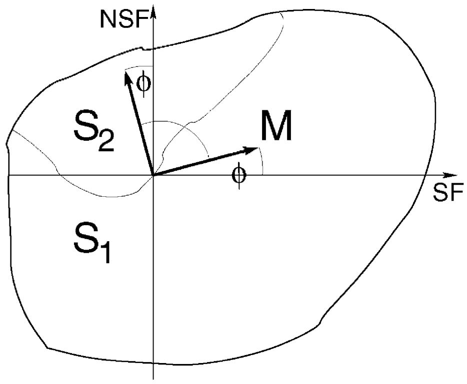

Fig. 4. A schematic view of the sample surface with two areas (S_1 and S_2) of 90° domains with magnetizations **M**.

samples can be expressed in the following form:

$$\frac{I_{\mathrm{NSF}}}{I_{\mathrm{SF}}} = \frac{x\sin^2(\phi_0 + \Delta\phi) + (1-x)\cos^2(\phi_0 + \Delta\phi)}{x\cos^2(\phi_0 + \Delta\phi) + (1-x)\sin^2(\phi_0 + \Delta\phi)}, \tag{1}$$

where $\phi = \phi_0 + \Delta\phi$, ϕ_0 describes the initial sample alignment and $\Delta\phi$ is the angle of the sample rotation about the normal to the surface.

The experimentally obtained values of $I_{\mathrm{NSF}}/I_{\mathrm{SF}}$ and the fit of Eq. (1) are presented in Fig. 5. The obtained values of the fitting parameters x and ϕ_0 are also shown in Fig. 5 for both samples. The broken line shows the calculated ratio of NSF to SF intensities in the case of a uniaxial sample (for which $x = 1$) with the same alignments with respect to the polarization direction.

In bulk EuS the easy axes lie along [1 1 1]-type directions, whereas, in the layered structures, due to the shape anisotropy, the magnetization directions are confined to the (0 0 1) growth plane of the layers. Due to the fourfold symmetry one can expect analogous symmetry in the distribution of domain magnetization directions. Our neutron reflectivity measurements performed in conjunction with rotating the samples about the axis normal to the reflecting surface essentially show the presence of a biaxial state with 90° domains. This would be in agreement with the crystallographic symmetry of the EuS layer, apart from the fact that the populations of the two types of domains are far from being equal. For both the, EuS/PbS and EuS/YbSe, samples more than three

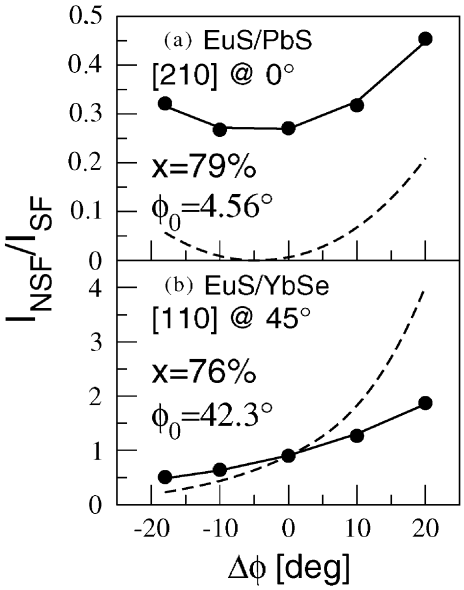

Fig. 5. NSF to SF intensity ratios as a function of the samples orientations with respect to the neutron polarization direction. Solid lines represent the fits of Eq. (1) to the experimental data. Broken lines shows calculated from Eq. (1) NSF/SF ratios for uniaxial samples (i.e., for $x = 1$) with the same alignment. The fitted values of ϕ_0 reflect the actual initial samples misalignment.

quarters of the sample (76% and 79%, respectively) belongs to one type of domain. Thus, this result shows that the fourfold symmetry of the EuS layers is, if not broken, then at least weakened as compared to the bulk crystal.

Moreover, it was found that the domain magnetizations in EuS/PbS and EuS/YbSe SL were aligned along different in-plane directions, the easy axes being $\langle 2\,1\,0 \rangle$ and $\langle 1\,1\,0 \rangle$, respectively.

The exact physical mechanism underlying the observed symmetry weakening is not yet clear. A number of mechanisms may contribute to the evolving magnetic anisotropy in thin films apart from the shape anisotropy. These might be anisotropic relaxation of strain induced by the lattice mismatch, nonisotropic steps on the substrate surface, or interfacial compound formation, but the source of the uniaxial component in our samples remains an open issue.

Acknowledgements

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